UCRL- 84574
PREPRINT

FUSION REACTOR NUCLEONICS:

STATUS AND NEEDS

J.D. Lee
Bernard A. Engholm
Donald J. Dudziak
Robert C. Haight

This paper was prepared for inclusion in the Proceedings of the Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Purssia, PA, October 14-17, 1980.

FUSION REACTOR NUCLEONICS: STATUS AND NEEDS*

J.D. Lee
Lawrence Livermore National Laboratory, University of California
B.A. Engholm
General Atomic Co.
D.J. Dudziak
Los Alamos Scientific Laboratory
R.C. Haight
Lawrence Livermore National Laboratory, University of California

SUMMARY

The national fusion technology effort has made a good start at addressing the basic nucleonics issues, but only a start. No fundamental nucleonics issues are seen as insurmountable barriers to the development of commercial fusion power. To date the fusion nucleonics effort has relied almost exclusively on other programs for nuclear data and codes. But as we progress through and beyond ETF type design studies the fusion program will need to support a broad based nucleonics effort including code development, sensitivity studies, integral experiments, data aquisition etc. It is clear that nucleonics issues are extremely important to fusion development and that we have only scratched the surface.

1. INTRODUCTION

The nuclear design and analysis challenges faced by neutron producing fusion systems are an important aspect of fusion development. Nucleonics is important to fusion because 80% of the energy release from the principal deuterium-tritium fusion reaction (DT) is the kinetic energy of 14 MeV neutrons. Also, DD fusion produces 2.5 MeV neutrons.

The abundance of fusion neutrons is a mixed blessing. Without them DT fusion would be impractial because transmutation of lithium by fusion neutrons is the only practical way we know of producing the tritium (T) fuel. The 14 MeV neutrons can also be used to generate excess neutrons for the production of additional transmutation products, such as U233. On the other hand massive amounts of materials are needed to utilize the DT neutron for breeding and production of useful thermal energy, and for shielding personnel, and sensitive components. Material damage and activation are also important side effects of fusion neutrons.

*Work performed under the auspicies of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

The fusion nucleonics effort is engaged in three principal activities: (1) near term experimental plasma hardware programs, such as TFTR and MFTF, where activation, biological shielding, magnet heating, and shielding sensitive diagnostic equipment from DD neutrons are the principal issues, (2)design of next generation fusion experiments, like ETF, characterized by having significant DT fusion power where shielding components such as super conducting (SC) magnets becomes an additional issue, and (3)conceptual design studies of commercial fusion reactors where the entire range of nucleonics issues are important.

Our objective for this paper is to give an overview of the status and needs of fusion nucleonics by discussing four areas:

1) Commercial Reactor Studies

2) The Engineering Test Facility (ETF)

3) Nucleonics Methods and Codes

4) Nuclear Data

More detailed treatment of nucleonics issues can be found in the 'Neutronics and Shielding' section of these proceedings.

2. COMMERCIAL REACTOR STUDIES

The development of commercial reactors requires successfully negotiating the entire gauntlet of nucleonics issues. General issues are:

Energy conversion -- conversion of the kinetic and potential energy of the 14 MeV DT fusion neutron to usable thermal energy.

Fuel production -- breeding of tritium to fuel the DT fusion reaction , and if desired to use excess neutrons to produce fissile fuel for fission reactors.

Shielding -- protection of sensitive components and personnel.

Radiation damage -- affects life time of materials.

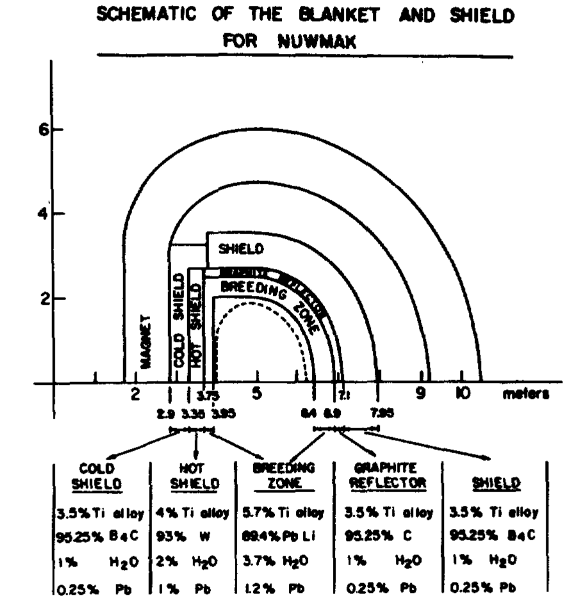

Figure 2-2

- Tritium breeding - 1.54
- Blanket/shield heating - 17.2 MeV
- Maximum neutron flux in NbTi superconductor - $7 \times 10^{15}/cm^2/y$
- Maximum dpa in Al stabilizer - $2 \times 10^{-6}/y$
- Maximum dose rate in epoxy insulators - 3×10^7 rads/y
- Nuclear heating in TF coils - 500W
- Activity - about 0.8 curies/W
- Dose rates one hour after shut down - 6×10^5 rem/hr inside and about 6mrem/hr outside

The NUWMAK design does a good job of achieving its nucleonic design goals. Examples of areas requiring further analysis are the effects of penetration in the blanket and shield and a more rigorous method of determining outside dose rates.

STARFIRE is a just completed advanced tokamak reactor design study done by a team from Argonne National Laboratory, McDonnell Douglas Astronautics Co., the Ralph M. Parsons Co., and the University of Wisconsin[2-2,3]. STARFIRE is a 3500MW-fusion (4000MW-thermal) machine with a major radius of 7m and an average neutron wall loading of 3.6 MW/m^2. An isometric view of STARFIRE is shown in Fig. 2-3.

Two unique nucleonics aspects of this design are: (1) The blanket uses a water cooled solid breeder ($LiAlO_2$, 40cm) behind a solid

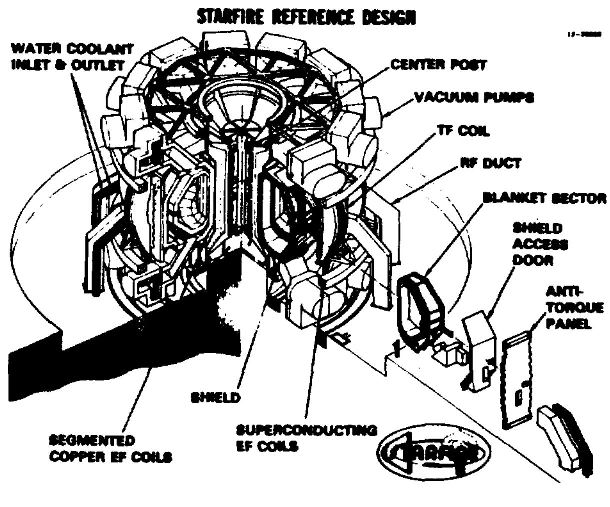

Figure 2-3

neutron multiplier (Zr_5Pb_3, 7cm) which is required to have adaquate tritium breeding. Its structure is austenitic stainless steel, with an assumed useful life of 20 MW/m^2. (2) Shield design played an important part in the evolution of the overall reactor design. Examples of this are the use of a limiter instead of a divertor for plasma control and exhaust, and rf for plasma heating instead of neutral beams. The limiter uses a 40 cm high toroidal slot in the outboard blanket which communicates circuitously with the vacuum pumps located around the top of the toroid. RF ducts also penetrate the blanket and shield in a circuitous manner manner. The inboard shield uses tungsten and boron carbide to protect the TF coils while requiring the least space (67 cm thick). This results in a maximum insulator dose of 5×10^9 rads in 30 years, maximum radiation induced resistivity in the Cu stabilizer of 5×10^{-10} ohm meters, and a critical current drop of 2% after 20 MWY/m^2 wall exposure. The outboard shield, in addition to protecting the TF coils, is designed to limit activation and resulting dose rate to allow for material recycling and hands-on maintenance.

Radiation streaming through ducts is an important aspect of the STARFIRE study. Nuclear heating of vacuum pump cryo panels is a concern but Monte Carlo calculations showed this should not pose problems, provided the duct length is greater than 3 m, at which the heating in SS panels is 0.5 kW/m^2. The 40 cm limiter slot increased the neutron flux at the vacuum port by 70%, the implication being that the cryopanel heating due to the limiter slot is not excessive. Neutron streaming out the rf ducts is also acceptable in that none of the dielectric windows receive a neutron flux of more than $10^{18}/cm^2/y$.

The Tandem Mirror Reactor (TMR) is a new

2-5 G. Carlson, et.al. 'Tandem mirror reactor with thermal barriers', LLNL Report UCRL-52836, Sept.1979

2-6 J. Lee, et.al. 'Progress Report on the Neutral Beam 'Hardening ' Study' LLNL Report UCID-18017, Oct.1978

2-7 F. Klinard, J. Nuc. Materials, 85-86, 1979, p. 393-404

2-8 T. Frank, et.al. 'Some Neutronic Aspects of Laser-Fusion Reactors' Proc. of the 1st Topical Meeting on the Tech. of Controlled Nuclear Fusion, Vol. 2 p101, April 10-18, 1974, San Diego

2-9 D. Dudziak, 'Neutron Streaming Calculations (in laser beam tubes), LASA Report LA 8135, July 1979, p. 57

2-10 W. Meier 'Two-Dimensional Neutronics Calculation for the HYLIFE Converter' LLNL Report UCRL-83595 Rev.1, Nov.1979, Accepted for publication in NUCL. TECH.

3. ENGINEERING TEST FACILITY

The Engineering Test Facility (ETF)[3-1] can be selected as a near-term, programmed example of fusion neutronics applications and needs. The preconceptual design phase has been in progress since October, 1979, under a team of laboratory/industry participants stationed principally at the ETF Design Center in Oak Ridge. Nuclear analysis for the design comes under the purview of the Nuclear Systems Branch, with General Atomic as the responsible laboratory.

The scope of work in ETF nuclear analysis includes establishing radiation criteria, making nuclear data and R&D assessments, performing radiation analysis and shield design, and providing neutronics and shield design input to the ETF Design Center. The shielding calculations and the R&D assessments are, of course, closely coupled and iterative. These R&D requirements can best be understood by reviewing some of the ETF neutronics concerns, shown in Figure 3-1.

ETF radiation analysis and shield design activities are directed toward the design of the inboard and outboard bulk shields; divertor coil shielding; bulk shield gaps and penetrations; duct shielding and shield shutters; component shields; remote handling equipment; casks; test cell building; and safety. Neutronics analysis of test, breeding, and power modules or blankets will also become important in the later stages of the design.

The ETF Mission Statement[3-2] states that "a design goal shall be to allow hands-on maintenance external to the toroidal field coil shield". This goal makes the outboard, duct, and component shielding design particularly challenging, especially with respect to materials selection and arrangement, and shield irregularities. The inboard bulk shield has the classical functions of protecting the TF coil copper stabilizer from excessive resistivity increase, the organic insulation from loss of strength, and the dewar and coil from excessive nuclear heating. Other shielding functions shown in Figure 3-1 are

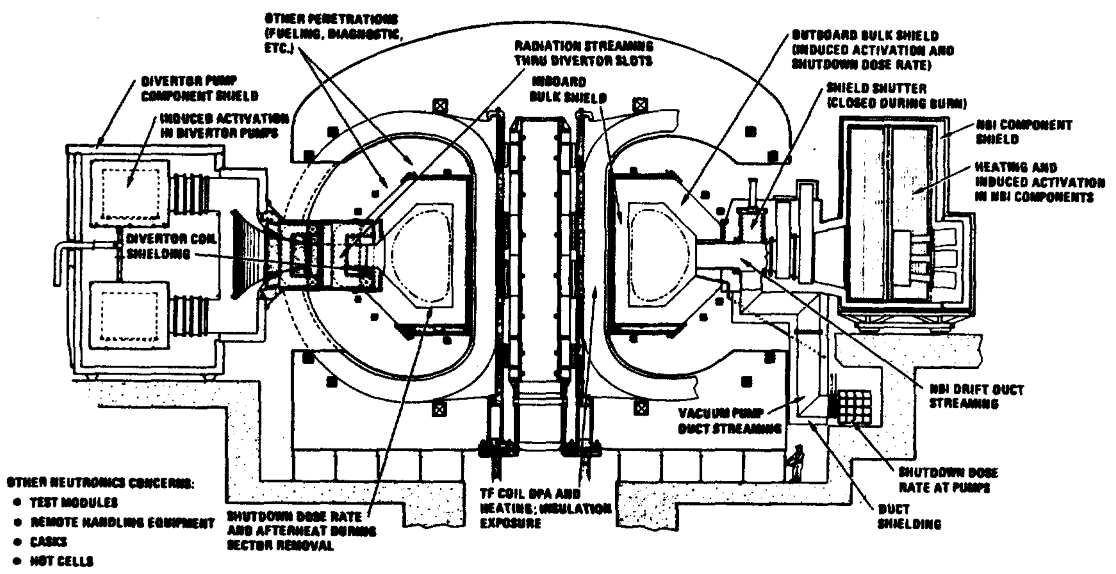

Fig. 3-1. ETF Neutronics Concerns

Table 3-1
ETF SUPPORTING R&D NEEDS-NUCLEAR ANALYSIS

Component, System, or Technology Decision	Date	Information and/or Technology Demonstrations Needed	Priority
1. Inboard bulk shield • composition • configuration • thickness	End of FY82	1.1 Neutron radiation effects on G10 and other insulators.	1*
		1.2 Effect of copper annealing	1*
		1.3 High-energy neutron cross sections - neutron emission and activation, and secondary gamma emission, for 9-15 MeV for ^{10}B, Ni, Cu, Fe, Cr.	1
		1.4 Sensitivity studies.	2
		1.5 Shield optimization code.	2
2. Outboard bulk shield • composition • configuration • thickness	End of FY83	2.1 Improved discrete ordinates/Monte Carlo coupling. [Also 1.3, 1.4, and 1.5.]	1
3. Divertor coil shielding • streaming • local heating & damage	End of FY83	3.1 Improve Monte Carlo variance reduction and simplify input.	2
		3.2 Complete THREETRAN code development.	2 or 3
		3.3 Additional cross sections for W, Ti, Ta.	1
		3.4 Integral experiment on advanced materials.	1
		3.5 Damage and activation cross sections for C, Ni, Fe, Cr.	1
4. Bulk shield gaps and penetrations • streaming • local heating & damage	End of FY82 (Conceptual) End of FY85 (Title I)	4.1 Develop neutron streaming computer code with improved semiempirical techniques.	2
		4.2 Integral experiments to validate calculational techniques for complex geometries.	1
		4.3 Improve acceleration techniques for discrete ordinates codes for streaming calculations.	2
		4.4 Generate parametric 14 MeV neutron gap streaming data**.	1*
5. Test modules Power module • heating • activation • damage • streaming • breeding	End of FY82 (Conceptual) End of FY87 (Title II)	5.1 Prototype tests in TFTR.	2
		5.2 Additional neutron cross sections for ^7Li, Pb, Al, etc. [Also, 3.2]	2
6. Duct shielding & shield shutter • streaming • activation of components • heating of components	End of FY82 (Conceptual) End of FY87 (Title II)	6.1 Develop more effective methods for dividing large transport problems into subproblems.	3
		6.2 Mockup experiment [Also 2.1]	?
7. Components shields • materials • thicknesses	End of FY82 (Conceptual) End of FY87 (Title II)	7.1 TFTR NBI radiation measurements (heating, activation)	1

NOTE: Remote handling equipment, casks, building, and safety have not been assessed in detail.

* Priorities assigned by author.
**Recent addition.

of Controlled Nucl. Fusion, King of Prussia, PA, 14-17 Oct. 1980.
3-4. W.T. Urban, et al., "Nucleonic Analysis of a Preliminary Design for the ETF NBI Duct Shielding", ibid.
3-5. M.A. Abdou, "Important Aspects of Radiation Shielding for Fusion Reactor Tokamaks", Proc. 5th Int. Conf. on Reac. Sh., Knoxville, April 1977.
3-6. P.H. Sager, et al., "First Wall-Shield Design Considerations for ETF", Proc. 4th ANS Topical Meeting Technol. of Controlled Nucl. Fusion, King of Prussia, PA, 14-17 Oct. 1980.

4. NUCLEONIC METHODS AND CODES

An assessment of the status and needs of nucleonic methods and codes must be indexed to the purposes for which they will be employed. Previous assessments have been performed in the context of either conceptual design studies,[4-1,2,3] or actual engineering design related to a potential construction project.[4-4] Presently, a canonical example of the latter case is the ETF Project discussed above, and it is primarily to such design efforts that this assessment is addressed. Most of the comments made in Ref. 4-4 with respect to nucleonic methods and codes, although at that time (1976) directed toward a possible Experimental Power Reactor (EPR), are equally applicable to the ETF. Also, experience with and planning for the ETF design effort have identified additional areas as noted in Table 3-1.

4.1. Transport Codes

All current nucleonic design and analysis efforts for both conceptual reactor studies and ETF employ either discrete-ordinates (generically and colloquially referred to as S_n) or Monte Carlo transport methods[a]. It is anticipated that these will continue in the ascendancy as the methods of choice during the next few years, with any new code development concentrating on evolutionary improvements of these two quite different, but complementing, approaches. Perhaps the most pressing immediate need is for a more effective marriage of the two methods. Recent work on the ETF neutral beam injector (NBI) and vacuum duct streaming/shielding[4-5] has demonstrated anew the importance of linking the two methods. Specifically, what is, in principal, a straightforward surface-source interface between the methods proved to be tedious and time consuming for the NBI duct analysis (cf. Fig. 4-1). This experience, repeated for the ETF vacuum duct, has led to plans for automation of much of the linking process. In the longer term, other hybrid S_n/Monte Carlo methods show promise for solving streaming problems, but no code development in this area is expected in the near future.

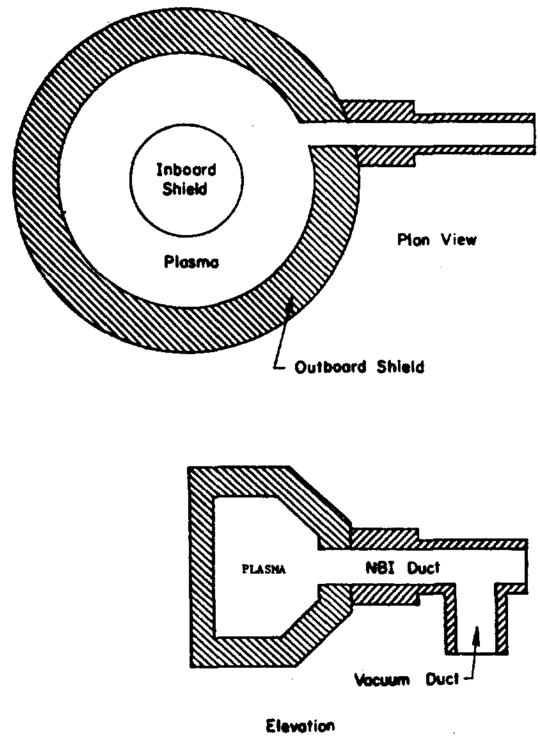

Fig. 4-1. Schematic views of the ETF NBI and vacuum duct geometries used for coupled Monte Carlo/S_n calculations.

Contemporary two-dimensional (2-D) S_n codes such as DOT, TRIDENT-CTR and TWOTRAN are generally capable of satisfactorily solving anticipated 2-D blanket/shield problems in a stand-alone mode, provided void streaming is not encountered. Future development of the specific fusion reactor code TRIDENT-CTR is expected in two categories: (1) Incorporation of numerical methods which modify the discrete-ordinates solution algorithm to ameliorate the void streaming problem, using methods now being developed; and (2) Evolutionary improvements and modifications in source options, boundary conditions, edit and graphics capabilites, etc., mostly in response to user requirements. Each major application of the code has led to additional capabilities to analyze problems that could not be anticipated at the time of initial code development. Referring again to the ETF, Fig. 4-2 illustrates the triangular mesh used to represent the portion of the NBI duct penetrating the outboard shield. By employing a stochastically-computed surface source on the duct shield surface and the first wall, the problem is readily soluble.

(a) A possible exception might be the use of point kernel codes for secondary shielding calculations.

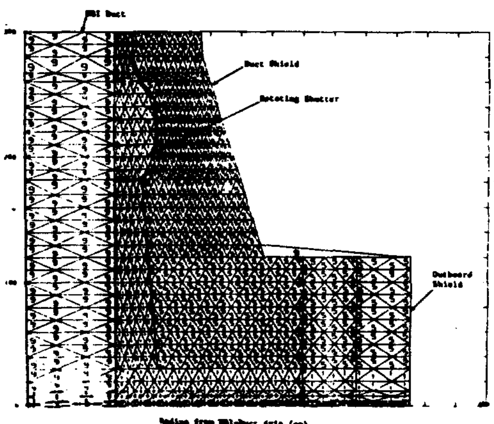

Fig. 4-2. Triangular mesh for TRIDENT-CTR model of the NBI-duct (region 9), outboard shields, and duct shield.

The situation with regard to 1-D S_n codes is generally satisfactory, ANISN and ONEDANT being the current generation. ONEDANT, which uses a free-field, mnemonic input, has a synthetic diffusion acceleration (DA) that significantly reduces computing time. While not particularly significant in 1-D, the computer time savings should be significant when the 2-D version (TWODANT) becomes publicly available. Finally, the ETF divertor coil shielding has demonstrated the renewed requirement for continuing development of 3-D S_n codes, which are currently still in a primitive state.

Present needs seem to be reasonably well satisfied by the current generation of Monte Carlo codes, primarily MCNP, MORSE, and TARTNP. Users seem to choose between the codes based mostly upon availability on a particular computing system rather than numerical capabilities, even though there are fundamental differences in numerical methodology which impact effects such as resonance self shielding and void streaming. A current need exists to examine some of the ramifications of multigroup versus continuous energy cross-sections, discrete versus continuous scattering angle, and other methodology differences in the three codes. These issues could have major impact on fusion reactor nucleonics, but the relatively limited use, let alone comparison, of these codes so far has left open the questions. Continual progress is being made in the improvement of variance reduction techniques as well as simplification of input (e.g., cf. Ref. 4-6), a need identified in Table 3-1. However, because of the complex nature of problems that causes one to resort to Monte Carlo methods, it does not seem realistic to expect the code to become as straightforward and foolproof for the casual user as are simple 1-D S_n codes. On the other hand, much remains to be done in automating some variance reduction techniques (e.g., surface splitting) and providing better guidance on their selection criteria, thereby making the codes more accessible to non-expert users. This latter point is quite important in view of the apparent increasing requirement for Monte Carlo analyses by many designers as fusion reactor concepts approach detailed design.

Coupling of S_n and Monte Carlo was discussed briefly above. It is important to add here the observation that for the foreseeable future this coupling will probably remain essential, for even with deterministic streaming methods and 3-D S_n codes, complex 3-D geometries may preclude application of deterministic methods. While the S_n calculations are necessary to predict detailed spatial/spectral distributions of flux and responses (e.g., the requirement for 3-D S_n in the divertor coil and its shielding), the transport of plasma neutrons in complex geometries with large vacuum chambers can now only be computed with Monte Carlo. Although techniques such as ray tracing to determine first collision sources are in principle applicable, in complex geometry they are almost equivalent to the Monte Carlo surface source technique already developed.[4-5]

A method commonly used to solve transport problems in ducts and voids is that of semi-empirical approximations, using geometric factors, albedos, etc. While such calulations are very approximate, they are invaluable when the designer is confronted with a myriad of penetrations and gaps which cannot all realistically be analyzed by Monte Carlo. Examples are gaps between vessels or other components and their shields, vacuum piping, primary coolant system pipes (especially He coolant), numerous instrumentation and diagnostics ports, etc. Codes for such analyses exist in the fission reactor industry, and must be adapted for fusion reactor neutron spectra and configurations. As noted in Table 3-1, the code(s) should ideally be available at the conceptual design stage. Related to these semi-empirical methods is the necessity to generate parametric "handbook" streaming data for fusion reactor spectra. Because shield modules will inevitably have inhomogenieties and construction gaps, empirical methods for designing offsets, etc. are required soon. The parametric data for such methods will require numerous, well chosen Monte Carlo analyses to cover the range of gap sizes, number of offsets, and shield module wall materials of immediate interest in the ETF.

4.2 Sensitivity and Optimization Codes

Methods and codes based upon simple perturbation theory presently exist at a mature state of development (SENSIT and SWANLAKE). Efforts related to sensitivity and uncertainty analyses in 1-D are now paced mostly by uncertainty data deficiencies, and in the case of secondary energy/angular distributions, by data formatting (cf. Sect. 5). Extension of sensitivity codes to 2-D is straightforward, and is under development.[4-7] Perhaps the major development that could impact sensitivity studies, but more importantly, shield optimization, is the development of tractable higher-order perturbation methods. Such development should be a long-term goal for fusion nucleonics.

4.3. Activation and Afterheat

Considerable effort has been expended to amass activation data libraries and to develop codes for computing activation levels. These codes and data vary from *ad hoc* developments to general purpose, fusion reactor oriented codes such as DKR[4-8] and RACC.[4-9] Since these codes have only recently become available with reasonably complete libraries, experience hasn't provided sufficient feedback to judge their adequacy. However, based upon previous experience with codes of more limited capability, it is reasonable to assume that the present generation codes are adequate for projected fusion reactor requirements.

4.4. Code Availability

Almost all the codes referred to in this review are publicly available via RSIC for selected computers and systems. Also, the authors are aware of the availability of the following codes on the NMFECC:

ANISN	DOT	MCNP	SENSIT
ONEDANT	TRIDENT-CTR	TARTNP	SWANLAKE
	TWOTRAN		

4.5 Summary and Conclusions

With the advent of fusion projects such as FMIT and ETF, which promise to go beyond the conceptual study stage in the near future, the need for some nucleonic codes and data is becoming pressing. Of particular concern are multi-dimensional streaming calculations in realistic duct configurations. Such complex calculations will require extensive development and confirmation of design methods, including benchmarks against experimental mockups. Existing Monte Carlo codes appear adequate for the task; development should be mainly in the areas of design protocol, improved variance reduction methods, and linking to deterministic transport codes. However, for the actual shield penetration and detailed spatial response computation, multi-dimensional discrete-ordinates codes will require added features. While present discrete-ordinates codes can usually treat geometric approximations adequately, shortcomings exist in the ability to accurately calculate streaming in large void regions. Thus, surface-source linking to Monte Carlo codes is currently required; or, alternatively, first-collision sources. Special needs of the ETF (e.g., divertor coil shielding) may also require further 3-D discrete-ordinates code development. Present generation codes are in any event taxing computer storage and time limitations, with resulting requirements for more efficient computational algorithms. Improved efficiency could result from better numerical differencing methods, acceleration schemes, or code features such as internal boundary sources and geometric modeling flexibility. Systematic numerical studies can also minimize the required meshes for acceptable accuracy.

This review of nucleonic methods and codes is of necessity limited in detail. Further discussion of some aspects of the subject is presented elsewhere in this Topical Meeting.[4-10]

RERERENCES

4-1. C. W. Maynard, "Overview of Methods and Codes for Fusion Reactor Nuclear Analysis," Trans. Am. Nucl. Soc., 23, 11 (1976).

4-2. Donald J. Dudziak, "Fusion Reactor Nuclear Analysis Methods and Applications," Proc. 8th Symp. on Fusion Technology," Noordwijkerhout, The Netherland, 17-21 June 1974. EUR 5182 e.

4-3. Donald J. Dudziak, "Selected Problems of Fusion Reactor Shielding: An Overview," Trans. Am. Nucl. Soc., 23, 627 (1976).

4-4. Donald J. Dudziak, "An Assessment of Nucleonic Methods and Data for Fusion Reactors," Proc. Sec. ANS Topical Meeting Technol. of Controlled Nucl. Fusion, Richland, WA, 21-23 Sep 1976, CONF-760935-83.

4-5. W. T. Urban, T. J. Seed and Donald J. Dudziak, "Nucleonic Analysis of a Preliminary Design for the ETF Neutral Beam-Injector Duct Shielding," Proc. Fourth ANS Topical Meeting Technol. of Controlled Nucl. Fusion, King of Prussia, PA, 14-17 Oct 1980.

4-6. "MCNP - A General Monte Carlo Code for Neutron and Photon Transport," Los Alamos Scientific Laboratory report LA-7396-M, Revised (1979).

4-7. Y. Seki, R. T. Santoro, E. M. Oblow, and J. L. Lucas, "Comparison of One- and Two-Dimensional Cross-Section Sensitivity Calculations for a Fusion Reactor Shielding Experiment," Nucl. Sci. Eng., 73 (1), 87 (1980).

4-8. T. Y. Sung and W. F. Vogelsang, "A Radioactivity Calculation Code for Fusion Reactors," University of Wisconsin report UWFDM-170 (1976).

4-9. Jungchung Jung, "Theory and Use of the Radioactivity Code RACC," Argonne National Laboratory report ANL/FPP/TM-122 (1979).

4-10. Donald J. Dudziak and P. G. Young, "Review of New Developments in Fusion Reactor Nucleonics," Proc. Fourth ANS Topical Meeting Technol. of Controlled Nucl. Fusion, King of Prussia, PA, 14-17 Oct 1980.

5. NEUTRON DATA

The microscopic description of neutron interactions with materials is the basis for the calculations of neutron transport and radiation effects. For fusion reactor applications, the data needs extend beyond those for fission reactors because of the larger neutron energy range (up to 15 MeV) and because of the wide variety of materials now under consideration in conceptual fusion reactor designs. For radiation test facilities such as the Fusion Materials Irradiation Test Facility, data ranging up to 50 MeV will be required both in the design of the facility and in the interpretation of experiments.

Present Status

The status of nuclear data and how well they meet the needs of fusion have been reviewed regularly and thoroughly in recent years.[5-1,2] Because of the enormity of this subject, only a brief and incomplete review can be given here.

The present nuclear data, both experimental and evaluated, constitute an extensive data base for the development of fusion energy. Experimental data are compiled routinely, exchanged through international agreements, and available from established centers such as the National Nuclear Data Center at Brookhaven National Laboratory. Evaluated data libraries such as ENDF/B-V and ENDL are also extensive and widely used.

The National Magnetic Fusion Energy Computer Center network and The Radiation Shielding Information Center serve as distribution points in the fusion community for processed data libraries and for processing and transport codes. For example, on the NMFECC network the ENDF/B-V evaluated library is available as processed data in the DLC series, the MATSX series and special libraries. In addition, a variety of processing codes operate in this network including NJOY and TRANSX. The major neutron transport codes in the NMFECC are ANISN, DOT-3.5, MCNP, Morse and TARTNP. The RSIC collection includes the extensive AMPX series as well as many codes and special libraries used for years in the design of fission reactors.

Nuclear data are therefore orders of magnitude better than when early fission reactors were designed. On the other hand, fusion reactor development requires an accurate and extensive data base because of the expense of early generation reactors and the necessary design conservatisms. Accuracy and completeness are the areas where the present data base can and should be judged.

Accuracy - The accuracy of the present nuclear data can be assessed by selected measurements of the fundamental cross sections or by integral experiments where the combined effects of several partial cross sections are tested. Examples could have been chosen here to illustrate that in certain important areas the data base is excellent. However, we strongly recommend against complacency towards the status of nuclear data and, to support our beliefs, have chosen important examples where the data base has serious failings.

Neutron interactions with ^{7}Li are important in nearly every fusion reactor design for tritium breeding via the ^{7}Li(n,n't) reaction and for neutron transport. Recently the accuracy of the ^{7}Li (n,n't) cross section data has been challenged by Swinhoe et al.[5-3] who obtained values 26% lower than the ENDF/B-IV evaluation and lower than most of the previous data. The preliminary data of Smith et al.[5-4] also are lower than the evaluation. The present status including the recent results is shown in Fig. 5-1.

The evaluated neutron emission data from ^{7}Li also represents the data poorly as shown by recent measurements by Drake et al.[5-5] (Fig. 5-2). In this case the treatment of the inelastic scattering does not take into account the level structure of ^{7}Li. With these new cross section data and a better representation of the nuclear physics, a new evaluation of neutron interactions with ^{7}Li is certainly required.

Integral tests of evaluated data are provided for example by the Integral Shield Benchmark Program at Oak Ridge National Laboratory and by the Livermore Pulsed Sphere Program. Again we present an example where the evaluation is not adequate to represent the experimental data, namely the neutron emission spectrum from a one-mean-free-path sphere of tungsten surrounding a 14-MeV neutron source (Fig. 5-3).[5-6] Because shields for the inner part of the toroidal field coils in a

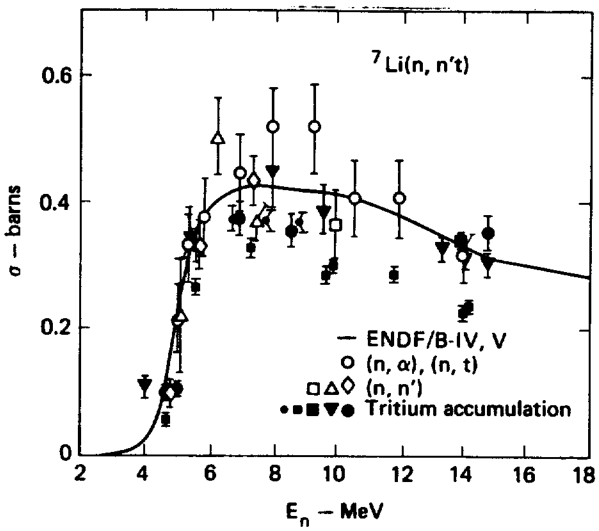

Fig. 5-1. Cross section for the ^{7}Li(n,n't) reaction. Recent data are from Swinhoe et al.[5-3] (small solid squares) and preliminary results of Smith et al.[5-4] (small solid circles). Other data are described in Ref. 5-2.

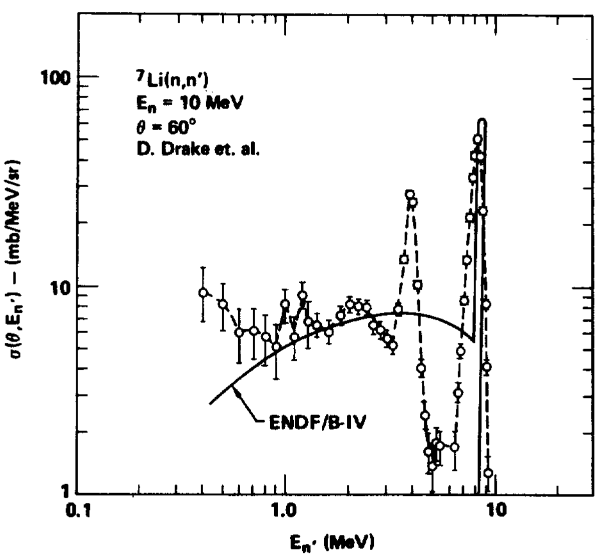

Fig. 5-2 Spectrum of neutrons emitted at 60° from 10-MeV neutron bombardment of ^{7}Li. Data are from Ref. 5-5.

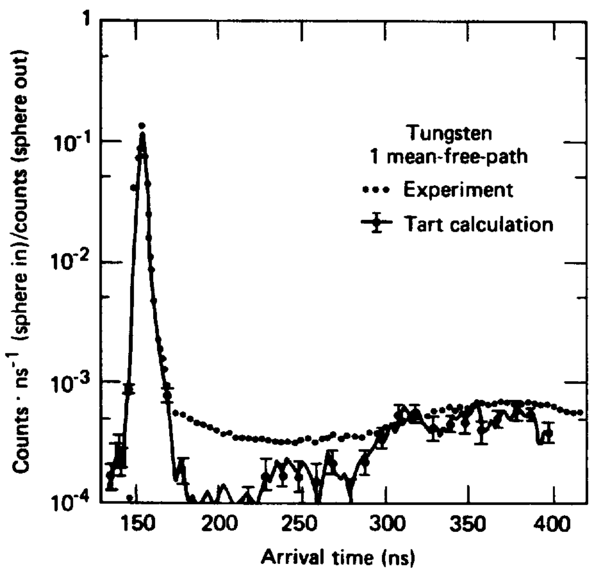

Fig. 5-3. Measured and calculated neutron emission (time-of-flight) spectrum from a 1-mean-free-path tungsten sphere surrounding a 14-MeV pulsed neutron source. The detector is 9.8m from the center of the sphere. The ENDF/B-V evaluated data library was used in the Monte Carlo calculation. The statistical uncertainties in this calculation are denoted by the error flags for representative points. The figure is adapted from Ref. 5-6.

Tokamak reactor must be small, tungsten is a candidate for this shield. Clearly, a better evaluation is required for this material.

Completeness - Of course, neither the experimental nor the evaluated data will cover all possible reactions at all relevant energies; to do so would be impossible experimentally and unrealistically expensive for the evaluations. Instead we should ask if the present data base is adequate for present and near-term future requirements. The two examples discussed here illustrate that active, on-going programs in data measurement and evaluation are required to fill the continually changing needs.

For the design of the Fusion Materials Irradiation Test Facility, cross section data were required for neutron energies up to 50 MeV. Few experimental data existed[5-7] when this facility was proposed and standard evaluations such as ENDF/B-V extended (and still extend) only to 20 MeV. The experimental situation was attacked by selected measurements at established facilities (see contributions in Refs. 8 and 9). The evaluations are being treated in an ad hoc manner using the new experimental results as they are available. Two symposia[5-8,9] have been convened to communicate progress in the experimental, theoretical, and evaluation areas for these newly required data.

Hydrogen and helium production in neutron reactions was also recently recognized as an important data need. Experimental programs (see contributions in Ref. 5-9) in these areas were directed toward fusion applications and the experimental data base has been markedly improved. Results[5-10] from one of these efforts are summarized in Fig. 5-4. Concurrently, a special gas production file is being set up for ENDF/B-V for the evaluated data.

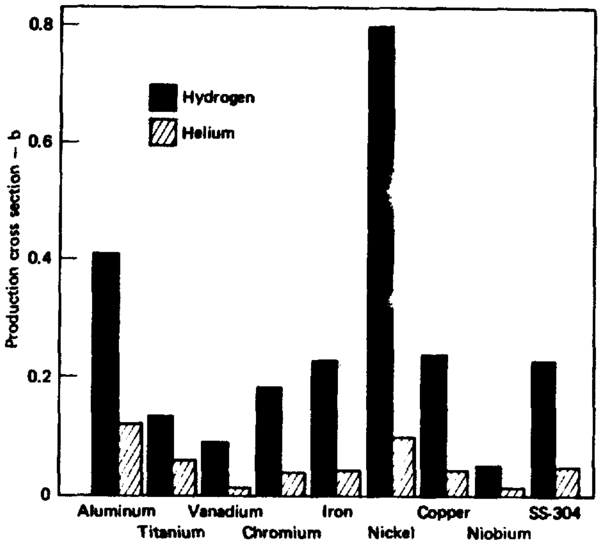

Fig. 5-4 Hydrogen and helium production cross sections at 15-MeV neutron energy from Ref. 5-10.

The response of the nuclear science community to these new needs has added much in these two areas of crucial importance to the development of fusion power. Yet new requirements will certainly arise regularly. One can imagine requirements for evaluated primary-knock-on atom specta, updated activation files, and transmutation files. More data for neutron energies between 14 and 50 MeV are required now for FMIT. And the completion of useful covariance uncertainty files is essential for sensitivity studies.

Future Prospects

There will certainly continue to be a great number of nuclear data needs for fusion. These needs will change with time, new types of data will be needed, new materials will be suggested, and greater accuracy will be required.

The ability of the nuclear science community to meet these needs will depend on available facilities, methods, and manpower in addition of course to operational support. The present facilities in the United States for measuring nuclear data have been constructed by agencies for fission reactor development, military application, physical research, and so forth. The capabilities to meet the data needs could depend therefore on the continued support from the other agencies. At present nearly all the major U.S. accelerators producing nuclear data for fusion are entering their second decade or older.

The development of improved methods, experimental, theoretical, and calculational will also be required. For example the need for more efficient neutron transport codes is clear as discussed in the preceding section. Nuclear reaction model codes must also be improved for calculating the wide range of required cross sections.

Finally, all of these developments depend on the availability of well-trained personnel. The factor of 3 drop in the production of doctorates in nuclear science in the last decade indicates a potential problem in this area.

We conclude that designers of fusion reactors will need steady improvements in nucleonics technology and that this area presents a great challenge for the development of economic fusion power.

References

5-1 J. C. Browne and P. W. Lisowski, "Status of High Energy Neutron Cross Section", Ref. 9.

5-2 R. C. Haight, "Neutron Cross Sections for Fusion", Proc. Int. Conf. on Nuclear Cross Sections and Technology, Knoxville, 1979 (to be published); and references therein.

5-3 M. T. Swinhoe and C. A. Uttley, "Tritium Breeding in Fusion", Proc. Int. Conf. on Nuclear Cross Sections and Technology, Knoxville, 1979 (to be published).

5-4 D. L. Smith, M. M. Bretscher, and J. W. Meadows, Argonne National Laboratory, (to be published).

5-5 D. Drake et. al., private communication (1979).

5-6 R. J. Howerton, "Data Testing Results for the ENDF/B-V Evaluated Neutron Data File", Lawrence Livermore National Laboratory report UCID-18731 (1980).

5-7 R. C. Haight, "Review of Neutron Data: 10 to 40 MeV", Ref. 8, p. 201.

5-8 Proc. Symposium on Neutron Cross Sections from 10 to 40 MeV, ed. M. R. Bhat and S. Pearlstein, Brookhaven National Laboratory report BNL-NCS-50681, Brookhaven, 1977.

5-9 Proc. Symposium on Neutron Cross Sections from 10 to 50 MeV, Brookhaven, 1980 (to be published).

5-10 R. C. Haight and S. M. Grimes, "Status of (n, charged particle) Measurements at LLNL", Lawrence Livermore National Laboratory report UCRL-84341 (1980), and Ref. 9.